

# TOP QUARK PRODUCTION CROSS-SECTION AT THE TEVATRON RUN 2

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The top quark pair production cross-section  $\sigma_{t\bar{t}}$  has been measured in  $p\bar{p}$  collisions at center of mass energies of 1.96 TeV using Tevatron Run 2 data. In the beginning of Run 2 both CDF and DØ  $\sigma_{t\bar{t}}$  measurements in the *dilepton* channel  $t\bar{t} \rightarrow WbW\bar{b} \rightarrow \ell\nu_\ell b\ell'\bar{\nu}_{\ell'}\bar{b}$  and in the *lepton plus jets* channel  $t\bar{t} \rightarrow WbW\bar{b} \rightarrow q\bar{q}' b\ell\bar{\nu}_\ell\bar{b} + \bar{\ell}\nu_\ell b q\bar{q}'\bar{b}$  agree with the NLO (Next-to-Leading-Order) theoretical predictions. The presence of a top signal in Tevatron data has been reestablished.

## 1 Introduction

To date, all direct measurements of top quark production have been performed by the CDF and DØ experiments at the Fermilab Tevatron collider in  $p\bar{p}$  collisions. At the Tevatron top quarks are produced predominatly in pairs through the QCD proceses  $q\bar{q} \rightarrow t\bar{t}$  and  $gg \rightarrow t\bar{t}$ . Top quarks can also be produced singly via the electroweak vertex  $Wtb$  with about half the cross section, but with final states difficult to extract from background.

In Run 1, at center of mass energies  $\sqrt{s} = 1.8$  TeV, the top pair production cross-section was expected to be  $5.19^{+0.52}_{-0.68}$  pb at  $m_{top} = 175$  GeV/ $c^2$ <sup>a</sup> with a 90% (20%) contribution from  $q\bar{q} \rightarrow t\bar{t}$  ( $gg \rightarrow t\bar{t}$ ). The precision of the measured cross-sections by the Tevatron from about 100 pb<sup>-1</sup> of data in Run 1 was approximately 25%<sup>b</sup>. The ratio of cross-sections at 1.96 TeV (Run 1) and 1.8 TeV (Run 2) is  $1.295 \pm 0.015$ , with an expected Run 2 cross-section of  $6.70^{+0.71}_{-0.88}$  pb with 85% (15%) contribution from  $q\bar{q} \rightarrow t\bar{t}$  ( $gg \rightarrow t\bar{t}$ )<sup>2</sup>. In Run 2a, with the increased center of mass energy and the expected integrated luminosity of 2 fb<sup>-1</sup> we should measure  $\sigma_{t\bar{t}}$  to better than 7% precision and observe single top production for the first time with a 20% precision on the cross-section measurement<sup>5</sup>.

<sup>a</sup>Results BCMN<sup>1</sup> updated in<sup>2</sup> taking into account the most recent determinations of systematic uncertainties in the extraction of the PDFs.

<sup>b</sup>The  $\sigma_{t\bar{t}}$  from all channels combined measurement by CDF<sup>3</sup> and DØ<sup>4</sup> was  $6.5^{+1.7}_{-1.4}$  pb for  $m_{top} = 176.1 \pm 6.6$  GeV/ $c^2$  and  $5.9 \pm 1.7$  pb for  $m_{top} = 172.1 \pm 6.8$  GeV/ $c^2$  respectively.

Within the SM the top quark decays almost exclusively into  $Wb$ . The  $t\bar{t}$  dilepton channel, where both  $W$ 's decay leptonically to  $e$  or  $\mu$ , has the smallest BR: 5%. In the so called “lepton plus jets” one  $W$  decays leptonically and the other hadronically giving a higher BR:  $\sim 30\%$ .

The Tevatron has delivered about  $170 \text{ pb}^{-1}$  in Run 2a up until January 2003. The detector upgrades have been extensive. CDF has expanded the silicon coverage and installed a new drift chamber. DØ has a new inner tracking (silicon and fiber trackers) with a new 2T superconducting solenoid. CDF has extended the electron identification to rapidity regions  $|\eta| > 1$  with a new plug calorimeter and the coverage of the muon systems.

## 2 $\sigma_{t\bar{t}}$ measurements in the dilepton channel

The background processes that mimic the top dilepton signature are Drell-Yan ( $Z^*/\gamma \rightarrow e^+e^-, \mu\mu$ ),  $Z \rightarrow \tau\tau$ ,  $WW/WZ$  and processes with a real lepton and a jet or a track *faking* a second lepton.

Dilepton selection starts with 2 high- $P_t$  ( $P_t > 20 \text{ GeV}/c$ )  $e$  or  $\mu$  oppositely charged. CDF requires both leptons to be well isolated from nearby calorimeter activity greatly reducing the *fake lepton*,  $Wb\bar{b}$  and  $b\bar{b}$  backgrounds. The dilepton invariant mass,  $M_{ee}$  or  $M_{\mu\mu}$ , is required to be outside the interval  $76 - 106 \text{ GeV}/c^2$  to reject  $Z \rightarrow \ell^+\ell^- X$  events. DØ discriminates  $t\bar{t}$  from  $Z$ 's in this interval by demanding larger  $\cancel{E}_T^c$  than in the region outside this interval.

A large  $\cancel{E}_T$  is required as a signature of the two  $W$  decay neutrinos. All backgrounds with real  $\cancel{E}_T$  contribution due to the presence of neutrinos are reduced. In addition CDF requires  $|\cancel{E}_T| > 50 \text{ GeV}$  if  $\Delta\phi(\cancel{E}_T, \ell \text{ or } j) < 20^\circ$  to eliminate instrumental contributions to the  $\cancel{E}_T$  due to mismeasured energies of lepton or jets<sup>d</sup> (see Figure 2).

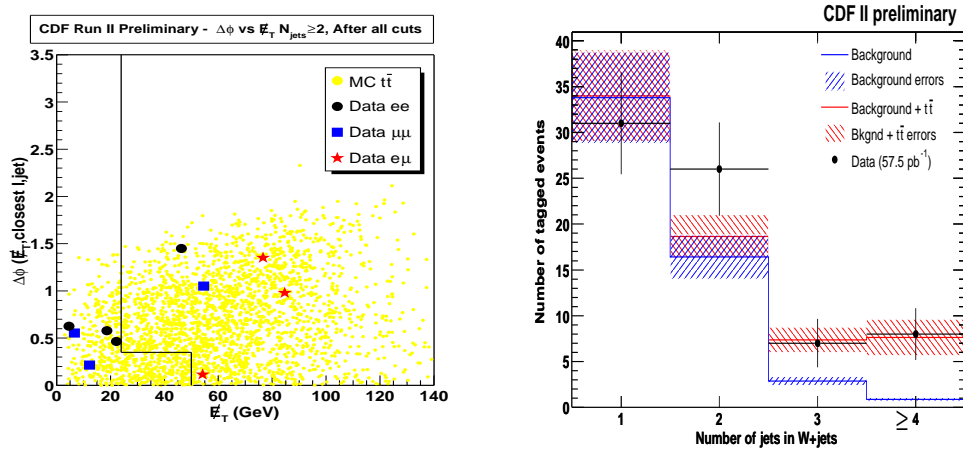


Figure 1: On the left side, the 5 CDF  $t\bar{t}$  dilepton candidates found in  $72 \text{ pb}^{-1}$  in the plane  $\Delta\phi(\cancel{E}_T, \text{nearest } \ell \text{ or } j)$  versus  $\cancel{E}_T$  in comparison with MC Herwig  $t\bar{t}$ . On the right side, number of events in the  $W + \text{jets}$  sample with at least one b-tag: the 3 and  $\geq 4$  jet bins are used to extract  $\sigma_{t\bar{t}}$ .

Two high energy jets are demanded as expected by the fragmentation of the top decay b quarks. The backgrounds with softer jets originating from QCD radiation are reduced. Finally, to enhance the signal-to-background ratio, large  $H_T$  is required<sup>e</sup>. The results from CDF and DØ are summarized in Tables 1 and 2.

## 3 $\sigma_{t\bar{t}}$ measurements in the lepton+jets channel

The CDF event selection required one  $e$  or  $\mu$  with  $P_t > 20 \text{ GeV}/c$ ,  $\cancel{E}_T > 20 \text{ GeV}$  and at least 3 high  $E_t$  jets. Cosmic rays, electron conversions, Drell-Yan and  $t\bar{t}$  dilepton events are removed.

<sup>c</sup> $\cancel{E}_T$  is the missing energy transverse to the beam direction.

<sup>d</sup> $\Delta\phi(\cancel{E}_T, \ell \text{ or } j)$  is the azimuthal separation between the vector  $\cancel{E}_T$  and the nearest lepton or jet.

<sup>e</sup> $H_T$  is the scalar sum of the transverse energy of the leptons, jets and neutrinos in the event.

Table 1: Run 2 CDF results in the  $t\bar{t}$  dilepton channel for a data sample of  $72\text{ pb}^{-1}$

Source	ee	$\mu\mu$	$e\mu$	$\ell\ell$
All Backgrounds	$0.103\pm 0.056$	$0.093\pm 0.054$	$0.100\pm 0.037$	$0.30\pm 0.12$
Expected $t\bar{t}\rightarrow\ell\nu_\ell b\ell'\bar{\nu}_{\ell'}\bar{b}$	$0.47\pm 0.05$	$0.59\pm 0.07$	$1.44\pm 0.16$	$2.5\pm 0.3$
Data	1	1	3	5

Table 2: Run 2 DØ results in the  $t\bar{t}$  dilepton channel

Source	ee	$\mu\mu$	$e\mu$
$\mathcal{L}\text{ pb}^{-1}$	48.2	42	33
All Backgrounds	$1.00\pm 0.48$	$0.6\pm 0.30$	$0.07\pm 0.01$
Expected $t\bar{t}\rightarrow\ell\nu_\ell b\ell'\bar{\nu}_{\ell'}\bar{b}$	$0.25\pm 0.02$	$0.3\pm 0.04$	$0.50\pm 0.01$
Data	4	2	1

To increase the signal-to-background ratio, CDF uses the Silicon Vertex Detector to identify the b-quark displaced vertices. A jet is b-tagged if it contains a secondary vertex with at least two charged tracks and  $\frac{L_{xy}}{\sigma_{xy}} > 3$ <sup>f</sup>. The efficiency for identifying at least one of the b quarks from  $t\bar{t}$  decays is about 45%, which is measured using  $t\bar{t}$  MC and corrected with a data to MC scale factor. The mistags from light quarks and gluon jets are evaluated using the negative rate of  $L_{xy}$  extracted from inclusive jet data and applied to W+jets data. The W/Z+heavy flavour:  $g\rightarrow b\bar{b}, c\bar{c}$  background is evaluated from W+jets data, the b tag rate and the Run 1 flavour composition in W+jets events. The non-W background is evaluated from W+jets data assuming it is flat in the plane of lepton calorimeter isolation versus  $\cancel{E}_T$ , and extrapolated from the low isolation and small  $\cancel{E}_T$  (non-W) region to the high isolation and large  $\cancel{E}_T$  (W dominated) region. Small contributions from diboson WW/WZ, Drell-Yan and single top production are evaluated from MC (see results in Table 3).

Table 3: Run 2 CDF results in the  $t\bar{t}$  lepton plus jets channel with displaced vertex tagging

Source	W+1jet	W+2jets	W+3jets	W $\geq$ 4jets
Background	$33.8\pm 5.0$	$16.4\pm 2.4$	$2.88\pm 0.05$	$0.87\pm 0.2$
SM Background plus $t\bar{t}$	$34.0\pm 5.0$	$18.65\pm 2.4$	$7.35\pm 1.4$	$7.62\pm 2.0$
Data before tagging	4913	768	99	26
Data ( $\geq 1b$ -tag)	31	26	7	8

The DØ *topological* analysis does not use b-tagging. First, a data sample enriched with W events is preselected by demanding a loose e or  $\mu$  with  $P_t > 20\text{ GeV}/c$ ,  $\cancel{E}_T > 20\text{ GeV}$  and a Soft Muon Tag veto. Then, the QCD background is evaluated from data for each jet multiplicity. In the  $e$ -channel this background is due to  $\pi^0$  and  $\gamma$  QCD compton in jets *faking*  $e$ 's and in the  $\mu$ -channel is due to real  $\mu$ 's from heavy flavour decays. The W +  $\geq 4$  jets background is estimated using the Berends scaling law. Finally, the topological cuts are applied to further reduce background: at least 4 jets, and large values of  $H_t$  and  $\mathcal{A}$ <sup>g</sup> (see results in Table 4).

The DØ *Soft Muon Tag* analysis has same preselection as the *topological* analysis. The topological requirements on  $H_t$  and  $\mathcal{A}$  are milder and at least 3 high- $E_t$  jets are required.

<sup>f</sup>  $L_{xy}$  is the distance in the transverse plane to the beam direction between the secondary vertex and the primary vertex.  $\sigma_{xy}$  is the resolution in the determination of  $L_{xy}$ .

<sup>g</sup> The Aplanarity  $\mathcal{A}$  measures the relative activity perpendicular to the plane of maximum activity.

Background is reduced by demanding one low momentum  $\mu$  in a jet coming from the semileptonic  $b$  decay (see results in Table 5).

Table 4: Run 2  $D\bar{O}$  results in the  $t\bar{t}$  lepton plus jets topologic analysis

	$N_W$	$N_{QCD}$	All BG	Exp Signal	$N_{obs}$	$\mathcal{L}(pb^{-1})$
e+jets	$1.3 \pm 0.5$	$1.4 \pm 0.4$	$2.7 \pm 0.6$	1.8	4	49.5
$\mu$ +jets	$2.1 \pm 0.9$	$0.6 \pm 0.4$	$2.7 \pm 1.1$	2.4	4	40

Table 5: Run 2  $D\bar{O}$  results in the  $t\bar{t}$  lepton plus jets Soft Muon Tag analysis

	All BG	Exp Signal	$N_{obs}$	$\mathcal{L}(pb^{-1})$
e+jets	$0.2 \pm 0.1$	0.5	2	49.5
$\mu$ +jets	$0.7 \pm 0.4$	0.8	0	40

## 4 Summary and conclusions

The  $t\bar{t}$  production cross-section in  $p\bar{p}$  collisions at  $\sqrt{s} = 1.96$  TeV has been determined from the number of observed top candidates in a given channel, the estimated background, the integrated luminosity and the  $t\bar{t}$  acceptance for a top mass  $175 \text{ GeV}/c^2$ <sup>*h*</sup>:  $\sigma_{t\bar{t}} = \frac{N_{obs} - N_{bkg}}{A \cdot \int \mathcal{L}}$ . All results are in agreement with the NLO prediction:  $6.70_{-0.88}^{+0.71}$  pb. Attributing the excess of events over the expected backgrounds to  $t\bar{t}$  production in the decay channels considered, we obtain the following first Run 2 results:

- CDF dilepton channels:  $\sigma_{t\bar{t}} = 13.2 \pm 5.9(stat) \pm 1.5(sys) \pm 0.8(lum)$  pb.
- CDF lepton plus jets channels:  $\sigma_{t\bar{t}} = 5.3 \pm 1.9(stat) \pm 0.8(sys) \pm 0.3(lum)$  pb.
- $D\bar{O}$  dilepton channels:  $\sigma_{t\bar{t}} = 29.9_{-15.7}^{+21.0}(stat)_{-6.1}^{+14.1}(sys) \pm 3.0(lum)$  pb.
- $D\bar{O}$  lepton plus jets channels:  $\sigma_{t\bar{t}} = 5.8_{-3.4}^{+4.3}(stat)_{-2.6}^{+4.1}(sys) \pm 0.6(lum)$  pb.
- $D\bar{O}$  all combined channels:  $\sigma_{t\bar{t}} = 8.5_{-3.6}^{+4.5}(stat)_{-3.5}^{+6.3}(sys) \pm 0.8(lum)$  pb.

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<sup>*h*</sup>For the latest results on top mass see <sup>6</sup>.